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INDUCED POLARIZATION AND RESISTIVITY

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INTRODUCTION

The purpose of this exposition is to outline the principles on which electrical prospecting techniques are based and then to show how these principles may be applied to assist in exploration for and evaluation of potential marine placer deposits. I shall start with basic definitions. With these I shall show what applications can be made in prospecting. Finally, I shall outline the present state of the art in marine electrical prospecting.

There are two electrical properties of interest in placer prospecting. These are resistivity and induced polarizability. The resistivity of a material is related to the degree of resistance offered by that material to the flow of electric current. The induced polarizability of the material is an indication of how well that material can store an electric charge for periods of a few seconds or so.

DEFINITIONS

Electrical resistivity is an intrinsic property of a material. It is normally measured by forcing electrical current through the material, and noting the value of the voltage which opposes the flow. Take for example the prism of Figure 1, which has a length L and a cross-section of area A. If a current I flows through the prism from end to end, and a voltage V is observed across the prism, then the resistance of the prism is, from Ohm's Law,

$$R = V/I.$$

If V and I are in volts and amperes respectively, then R is in ohms. To correct for the shape of the prism, we first obtain the current density by dividing the current by the cross-sectional area of the prism,

$$\text{Current Density} = I/A.$$

If A has units of square metres, then the current density is in amperes per square metre. To determine the distribution of voltage along the prism, we divide the total voltage V by the length L of the prism to obtain the electric field.

$$\text{Electric Field} = V/L$$

If L has units of metres, then the electric field has units of volts per metre.

Now to obtain the resistivity of the material, we replace the total voltage by the electric field, and the total current by the current density:

$$\text{Resistivity } \rho = (V/L) \,/\, (I/A)$$
$$= (V/I)(A/L)$$
$$= RA/L.$$

Thus if V and I are in volts and amperes respectively, and the distances are in metres, then resistivity is in units of ohm-metres.

Induced polarization (IP) is also an intrinsic property of a material. It can be determined in several ways; each method gives rise to a different but equivalent quantity. IP effects can be measured in terms of percent frequency effect (change in resistivity with measurement frequency), phase angle (between transmitted current and received voltage) or chargeability. Both percent frequency effect (PFE) and phase angle are measured with low-frequency alternating current, and are thus known as frequency-domain measurements. Chargeability is measured with pulsed direct current, and is known as a time-domain measurement.

We will consider the measurement of chargeability as an example. If, as in Figure 1, we put a switch in the wire leading to our prism, we can allow current to flow for a period of time. If we then interrupt the current flow, and observe the voltage across the prism closely, we will observe that it will not fall immediately to zero. Instead it falls almost instantly to some very small value, and then slowly falls away from that value to zero. We call the voltage observed during current flow the primary voltage, and that observed after current turn-off the secondary voltage. Because the secondary voltage is much smaller than the primary voltage, it is generally measured in millivolts. Traditionally the secondary voltage is integrated or averaged over some fixed period of time. If we carried out careful experiments varying the initial current, we would find that the integrated secondary voltage is proportional to the primary voltage. The ratio of the integrated secondary voltage to the primary voltage observed before current interruption is called the chargeability.

$$M = 1/V_p \int_{t1}^{t2} V_s dt,$$

where V_p is the primary voltage in volts,
V_s is the secondary voltage in millivolts,
and M is the chargeability in millivolt-seconds/volt or milliseconds.

In some cases the measurement is normalised with respect to the time over which the secondary voltage is integrated. In this case the chargeability becomes

$$M = 1/(V_p(t2-t1)) \int_{t1}^{t2} V_s dt,$$

where M is the chargeability in millivolts/volt.

In a typical IP measurement, the current is allowed to flow for several seconds before interruption, and the secondary voltage is integrated over about one second. The measurement is repeated a number of times with the current flowing in alternating directions, and the results are averaged.

WHY MEASURE RESISTIVITY AND CHARGEABILITY?

The values of resistivity and chargeability can give information about the materials in which they are measured.

The resistivity of a soil is determined primarily by two properties. The first is the size and composition of the component materials, and the second is the resistivity of the fluids in the pores. On land, for example, the resistivity of common soils and rocks (Figure 2, after Culley et al., 1975) varies systematically over several orders of magnitude. Coarse-grained materials such as sands and gravels can have resistivities of several hundred to several thousand ohm-metres, while clays and marls can have values as low as a few ohm-metres. While there is considerable overlap in values for any range of grain size, a general trend of decreasing resistivity with decreasing grain size is apparent.

In salt water, pore fluids are generally much more conductive than on land, and, as a result, all the values of resistivity are reduced, and the range of variation is compressed. Scott and Maxwell (1990) show that, at least in the Beaufort Sea, the grain size of seabed materials can be deduced from the interpreted electrical resistivities, even though the range of variation is less than fifty percent instead of several orders of magnitude.

In general, then, resistivity values observed within soils both on land and in the sea decrease with decreasing grain size. In the sea the range of variation is much reduced, but differentiation of coarse-grained from fine-grained materials is still feasible. With experience in a given area, and a certain amount of control, it is possible to map variations in grain size of bottom materials by mapping variations in resistivity values.

On land, the presence of metals or metallic particles in a material gives rise to strong IP effects. IP effects arise at the interfaces between these metallic particles and the pore fluids (Telford et al.,1990). The metallic particles conduct electricity by the movement of electrons, while the pore fluids

conduct electricity by the drift of charged ions. Current flow across the interface between a metallic particle and a pore fluid thus requires discharge of a charged ion. Since this takes an appreciable time, there is a buildup of ions waiting in the fluid to be discharged. When the current is interrupted, these ion concentrations diffuse back to their equilibrium positions; this diffusion results in the time-dependent voltage seen after interruption of the current. The strength of an IP response thus reflects the surface area of the particles in contact with the pore fluid, rather than the particle volume.

On land, the common minerals giving rise to IP effects include graphite, serpentinite, sometimes magnetite, metallic sulphides such as pyrite and chalcopyrite, and some other minerals such as ilmenite. IP measurements in salt water (Wynn, 1988) indicate that such measurements can be of interest in placer exploration. In Wynn's work, the mineral giving rise to IP effects is ilmenite. Figure 3, after Wynn (1988) and Scott (1991), shows the strength of IP responses as a function of ilmenite content. Although Wynn's field surveys were in salt water, the measurements shown in Figure 3 are in tailings saturated with fresh water. Also shown in Figure 3 are measurements (Scott, 1991) of IP responses for small amounts of ilmenite in marine sediments. While the magnitude of the responses is reduced, there is still a relationship between small percentages of ilmenite and the observed IP effect. Wynn's and Scott's studies suggest that in the marine environment, a few percent of ilmenite can be detected by IP measurements. At that level the concentration of ilmenite is useful even as a tracer in many placers. Study of marine IP responses is continuing both under Wynn at the United States Geological Survey and with Scott at C-CORE.

Field surveys have shown that resistivity measurements can give information on the grain size of bottom sediments, and thus allow the identification of areas of coarser materials. These areas presumably have a better possibility of containing concentrations of placer minerals. If the target is sand and gravel, then resistivity surveys can help to outline the most interesting areas. If the target is a placer deposit, then resistivity measurements can help to outline the most attractive areas in terms of textures, and IP measurements can help to map the distribution of ilmenite, and thus, by association, of other economic placer minerals.

SURVEY TECHNIQUE

Figure 4 shows in schematic form the layout of a marine survey system, as used by Scott and Maxwell (1990). Measurements are made by injecting electric current into the water and sub-bottom materials, and sensing the resulting voltage distribution at the surface. Contact with the water is made through connections called electrodes which are mounted on a buoyant cable called a streamer. Typically there are two current electrodes, nearest the vessel, and two or more (seven in Figure 4) electrodes for sensing the voltage distribution at increasing distances from the current electrodes. The sensing electrodes are known as potential electrodes.

The current electrodes are made of metal, usually lead or copper, with a large surface area to reduce the resistance of the connection with the water. The potential electrodes are usually non-polarising. Common electrodes of this type are constructed with a metal in the centre, surrounded with a saturated

solution of a salt of the metal. The solution is contained within a porous membrane which allows diffusion of ions across it. Figure 5 is a schematic representation of such an electrode. For fresh-water surveys, potential electrodes have used copper as the metal, and copper sulphate as the salt. In the marine environment, a variety of electrodes has been used. The electrochemical systems include copper/copper sulphate (Scott and Maxwell, 1990), silver/silver chloride (Corwin, 1985), and lead/lead chloride (Cox et al, 1981; Scott, 1991). Systems which involve a chloride ion have an advantage in salt water. The lead/lead chloride electrodes are saturated with sodium chloride as well as lead chloride during manufacture.

A transmitter on the vessel generates the alternating direct-current waveform which is put into the water through the current electrodes. The strength of the current is monitored for recording by computer. A receiver on the vessel detects the resulting potentials, also passed on for recording by computer. With such a system, one can determine, from the measurements for each pair of adjacent potential electrodes, a value of resistivity during current flow, and a value of chargeability between current pulses. These are called apparent resistivity and apparent chargeability values, because they represent values averaged through the water and bottom sediments.

With the marine electrical system, it is useful to obtain as much additional information as possible. Scott and Maxwell (1990) used two seismic systems of different penetration capabilities, and provided for a magnetometer whose readings would also be recorded by the computer. The seismic information is extremely useful in constraining the interpretation of the survey results. For placer-related work, the magnetometer could also offer useful information, if magnetite were expected to be in the suite of placer minerals.

To carry out a survey, one tows the streamer along selected lines, measuring apparent resistivity and chargeability values at close intervals, and operating the seismic systems and magnetometer as well. Some form of navigation is required, to record the vessel track.

It would be possible to perform a "shoestring" survey, in which standard equipment was used as much as possible. Such a system could employ a typical terrestrial IP transmitter, operated at its maximum output power. A terrestrial IP receiver, single or multi-channel, could also be used. Some form of special electrodes would be necessary still, but instead of a buoyant streamer, one could lay a cable on the bottom. With such a system, the cable would have to be placed along the seabed for each measurement and then either recovered or dragged to the next point. Production would be much slower than for a system capable of reading while in motion. In some situations this might be considered acceptable.

Once the distributions of apparent resistivity and chargeability are determined, it is necessary to translate the apparent values into estimates of the intrinsic values of the materials, and then to correlate the intrinsic values with the geological characteristics of the materials. Estimating the intrinsic values of the electrical properties is usually done with the aid of a set of type curves, or increasingly with computer-based modelling schemes which are commercially available. Sub-bottom structure interpreted from the seismic survey is incorporated in the interpretation.

Correlations between the intrinsic values of resistivity and IP and the geological properties are based on experience in a given area, and depend heavily on the available geological controls such as results of drilling and sampling.

Figure 6 (after Scott and Maxwell, 1990) is an example of a combined interpretation prepared for an area in the Beaufort Sea. The survey employed acoustic systems as well as the electrical resistivity system. The purpose of the survey was to look for sand and gravel suitable for use in construction of artificial islands on which to carry out deep-well drilling. The results indicated the presence of sand in some parts of the area, which was subsequently used for island construction. In addition, the results indicated the depth to permafrost in the survey area. In permafrost, much of the pore fluid is frozen, and the resistivity is consequently much higher that when the material is in an unfrozen state.

PRESENT STATUS AND FUTURE OUTLOOK

In fresh water, both resistivity and IP surveys have been carried out (see for example Dyck et al, 1983), and the method is available for commercial surveys directed towards mineral exploration and geotechnical applications. In salt water, resistivity surveys have been employed to map permafrost and identify sand and gravel (Corwin, 1985; Scott and Maxwell, 1990). One successful IP survey has been described in salt water (Wynn, 1988); high IP responses were correlated with the presence of ilmenite in the seabed sediments. The method is not yet in common use, but research is in progress.

Within the next few years it is likely that marine resistivity and IP surveys will become an accepted tool in the search for offshore sand and gravel, and in the appraisal of offshore placer deposits. Their most efficient employment will be in conjunction with acoustic sub-bottom profilers and possibly with a magnetometer.

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Figure 1. Schematic representation of measurement of electrical resistivity and chargeability.

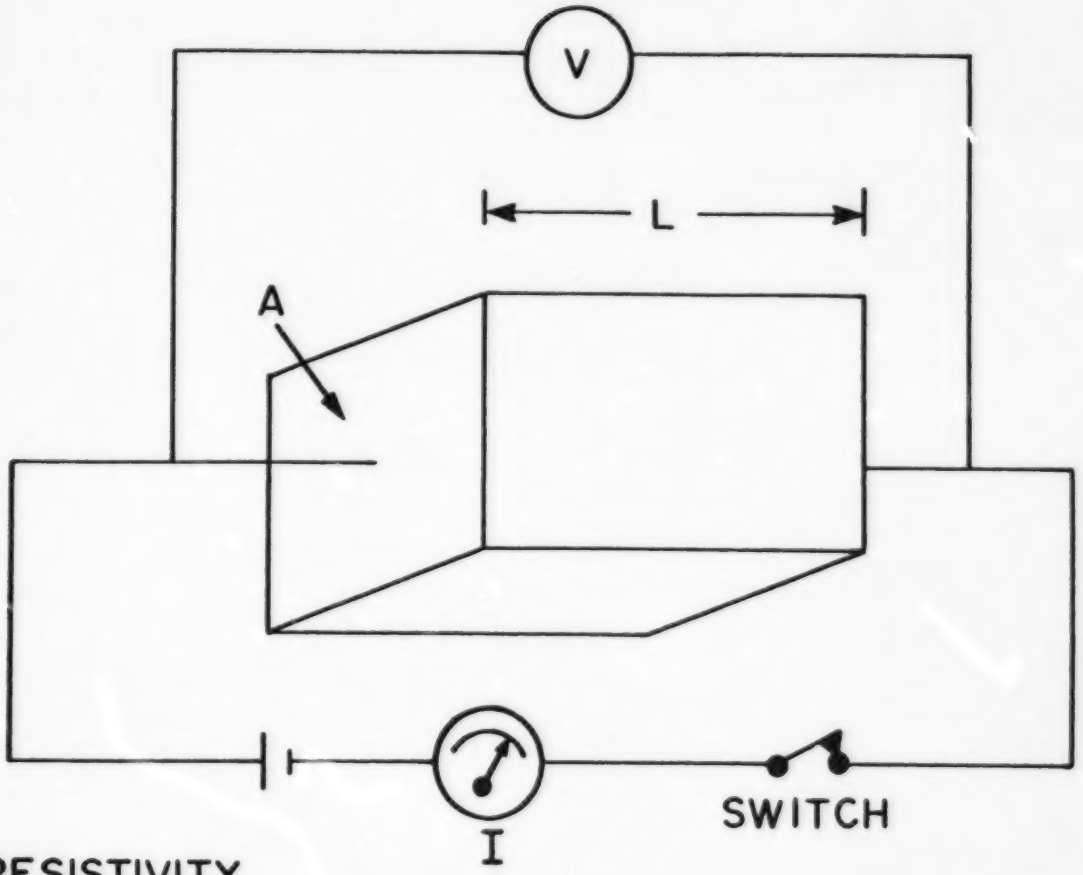
Figure 2. Resistivity values of common materials, after Culley et al. (1975)

Figure 3. Induced polarization of ilmenite-bearing materials, after Wynn, 1988 and Scott, 1991. Wynn measured phase angles associated with IP responses; his values are in milliradians of phase shift between transmitted current and received voltage. Scott's measurements are in millivolts per volt; the vertical scale is approximately equivalent.

Figure 4. Typical marine survey system, after Scott and Maxwell, 1990.

Figure 5. Sketch of potential electrode construction.

Figure 6. Results of resistivity survey in Beaufort Sea, after Scott and Maxwell, 1990. The central zone of higher resistivity (ρ_1=2.3 - 2.6 ohm-m) was mined to yield sand and some gravel for island construction. One drill hole in the same area intersected permafrost at a depth within four metres of the depth interpreted in this profile. The seismic survey showed a reflector (dashed line) which correlated well with the interpreted depth to permafrost in the central area. Permafrost resistivity values ranged from <50 to >500 ohm-m.



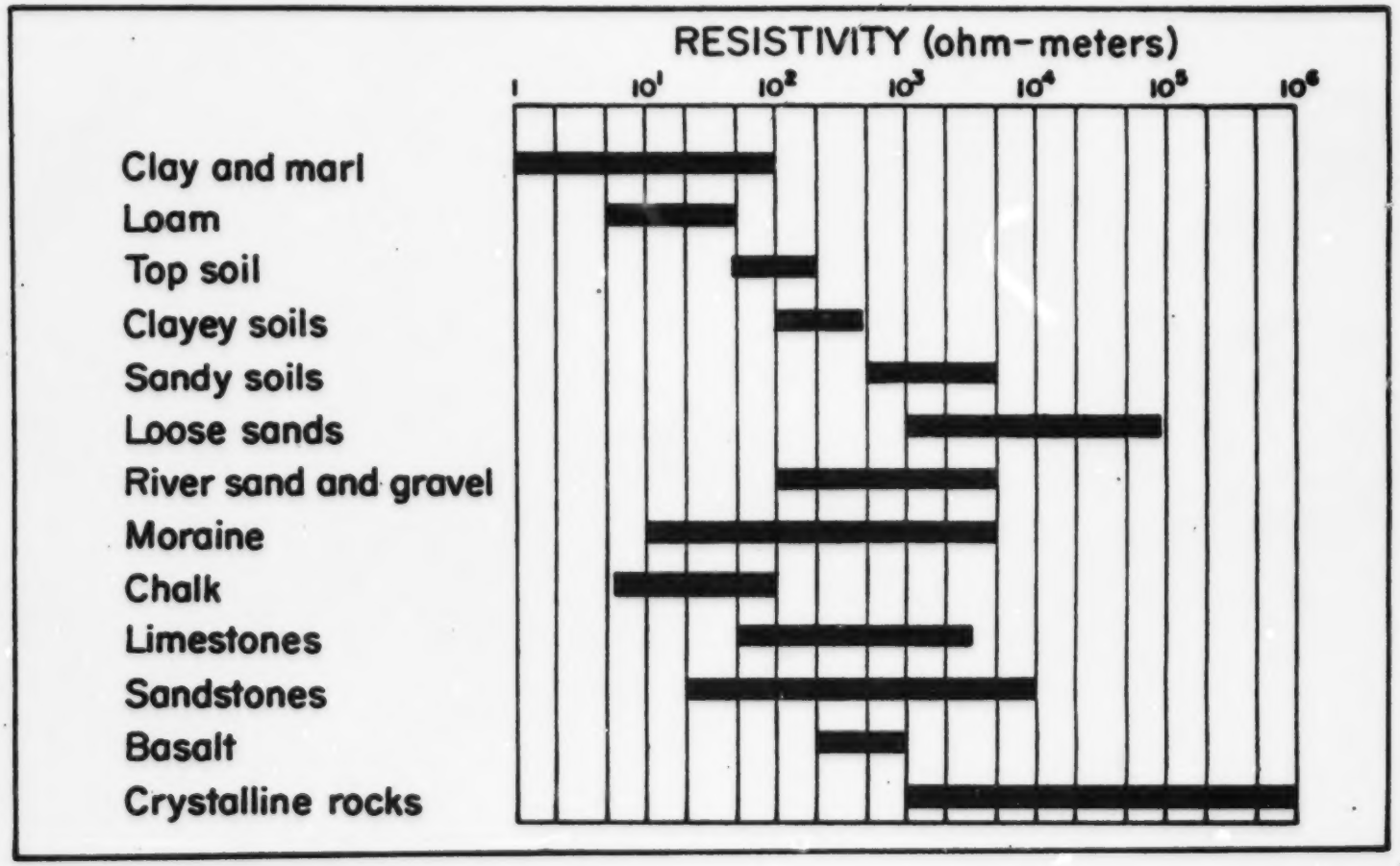
RESISTIVITY

$$\rho = \frac{V}{I} \cdot \frac{A}{L}$$

OHM-m (Ω-m)

OHM m

Figure 1


RESISTIVITY (ohm-meters)
1
10¹
10²
10³
10⁴
10⁵
10⁶
Clay and marl
Loam
Top soil
Clayey soils
Sandy soils
Loose sands
River sand and gravel
Moraine
Chalk
Limestones
Sandstones
Basalt
Crystalline rocks

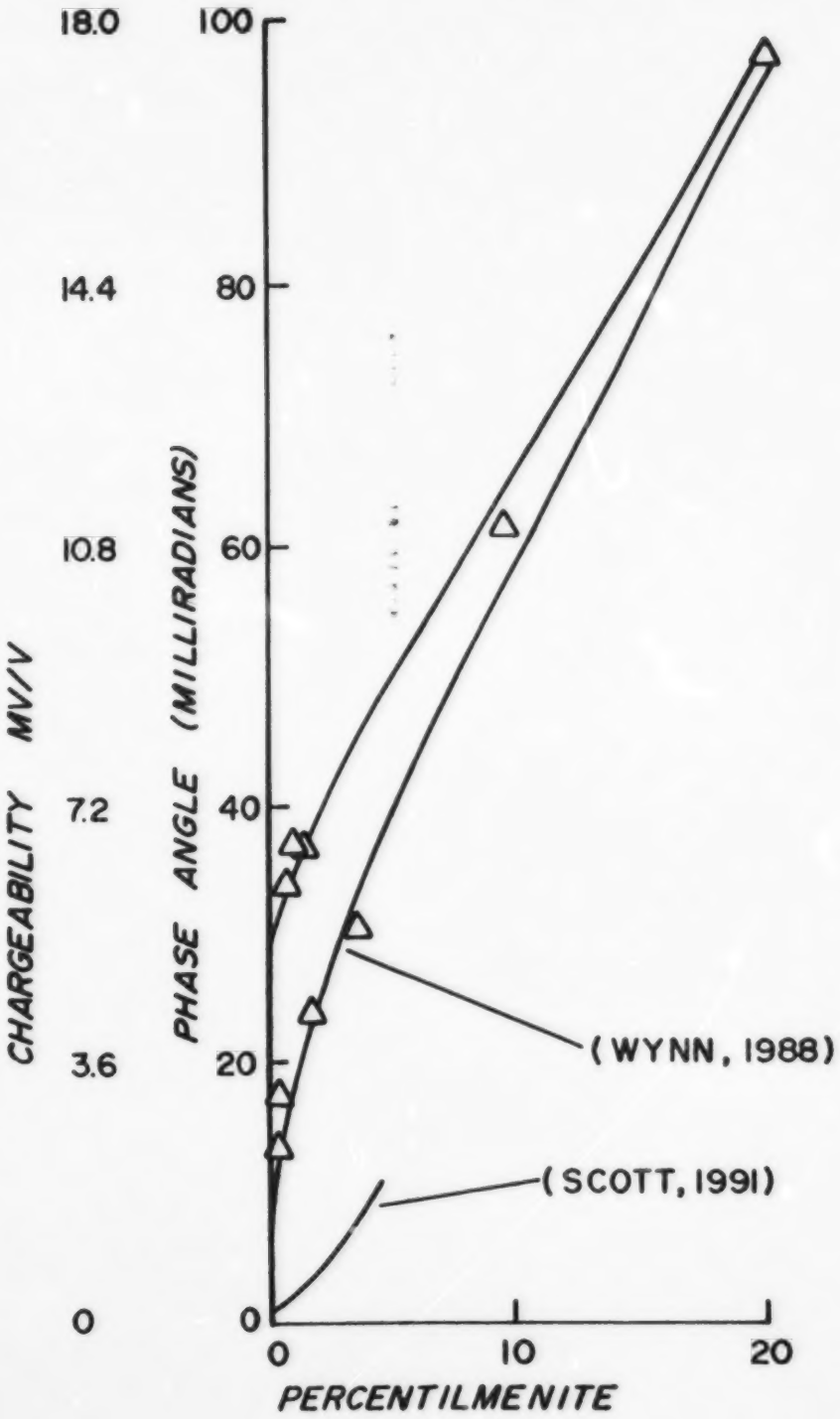
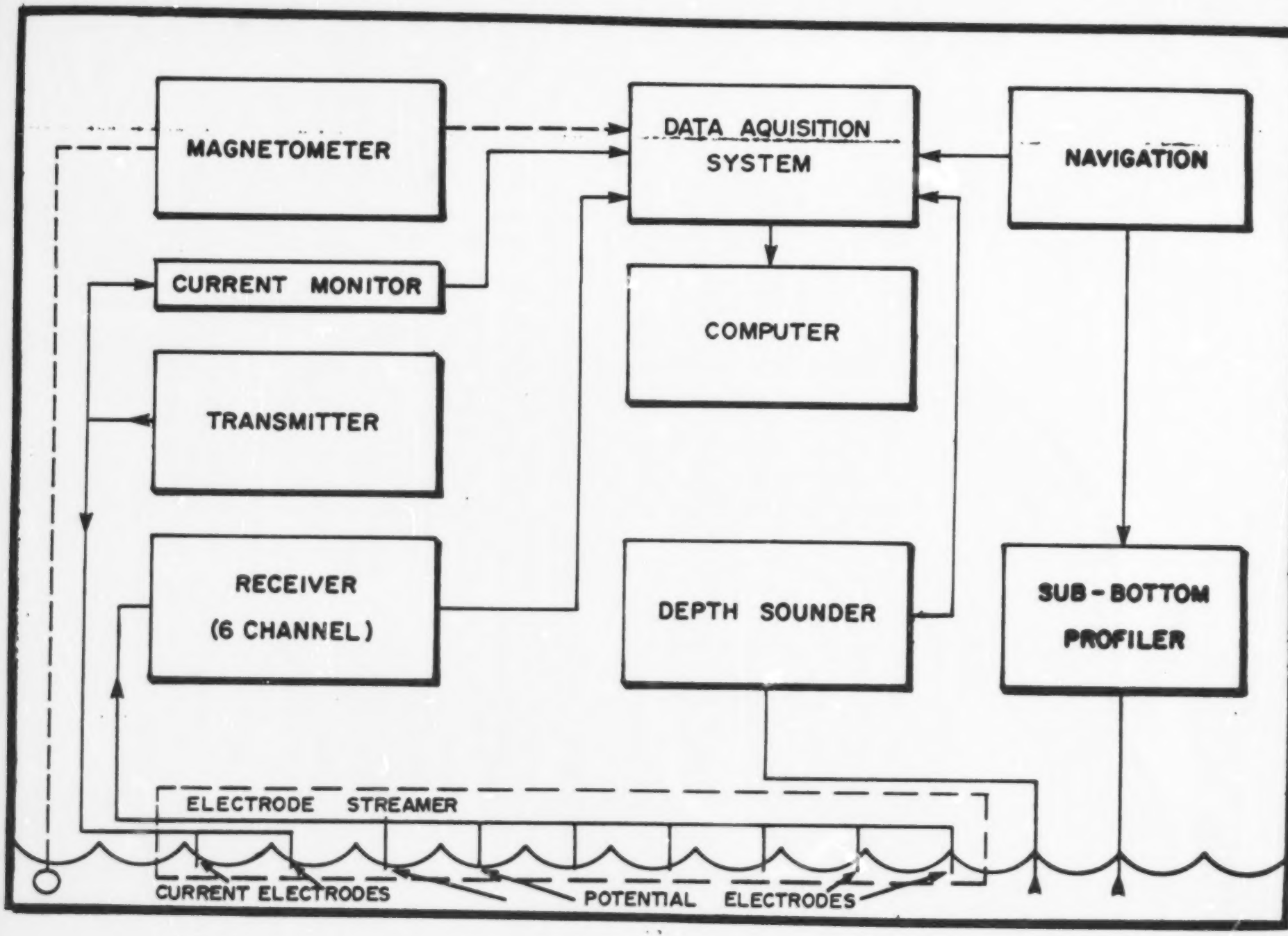
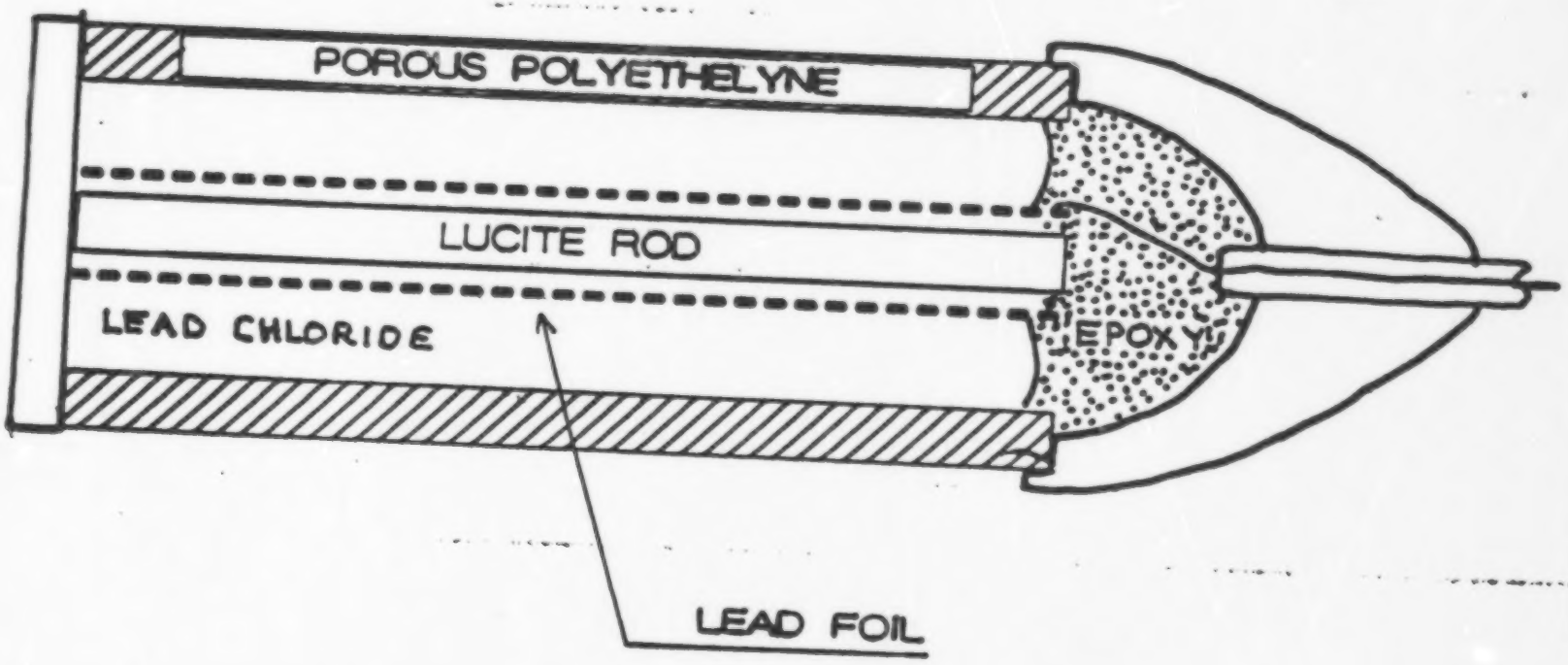

18.0
14.4
10.8
7.2
3.6
0
CHARGEABILITY MV/V
100
80
60
40
20
0
PHASE ANGLE (MILLIRADIANS)
0
10
20
PERCENTILMENITE
(WYNN, 1988)
(SCOTT, 1991)

Figure 3


MAGNETOMETER
DATA AQUISITION SYSTEM
NAVIGATION
CURRENT MONITOR
COMPUTER
TRANSMITTER
RECEIVER (6 CHANNEL)
DEPTH SOUNDER
SUB-BOTTOM PROFILER
ELECTRODE STREAMER
CURRENT ELECTRODES
POTENTIAL ELECTRODES

ELECTRODE DESIGN

Figure 5



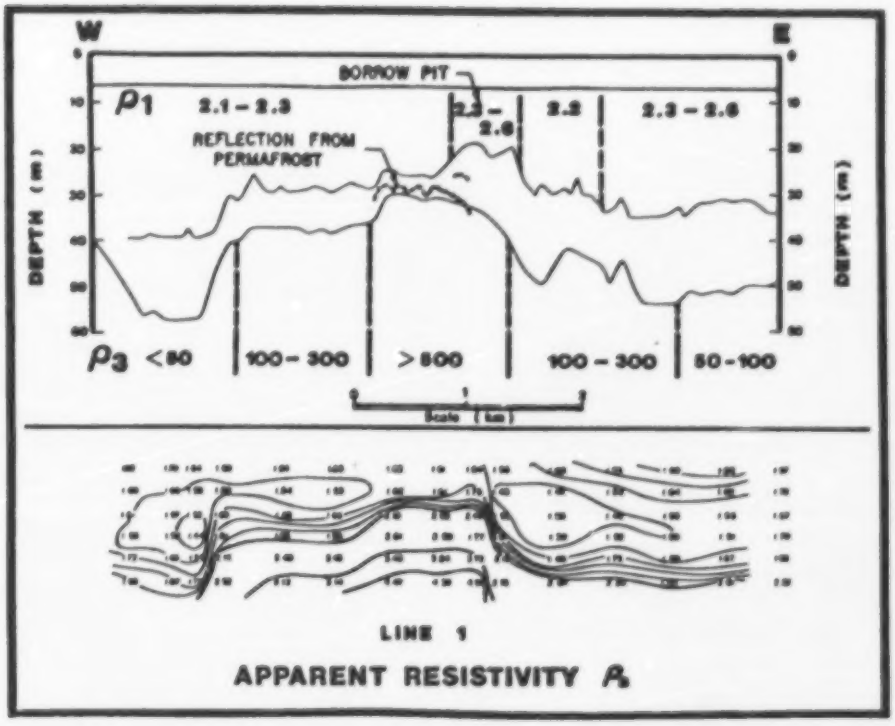

W
E
BORROW PIT
ρ_1
2.1 – 2.3
2.3 – 2.6
2.2
2.3 – 2.6
REFLECTION FROM PERMAFROST
DEPTH (m)
DEPTH (m)
ρ_3 <80
100 – 300
>800
100 – 300
50 – 100
Scale (km)
LINE 1
APPARENT RESISTIVITY ρ_a

Figure 6